QCD and the Strong Force

Joey Huston

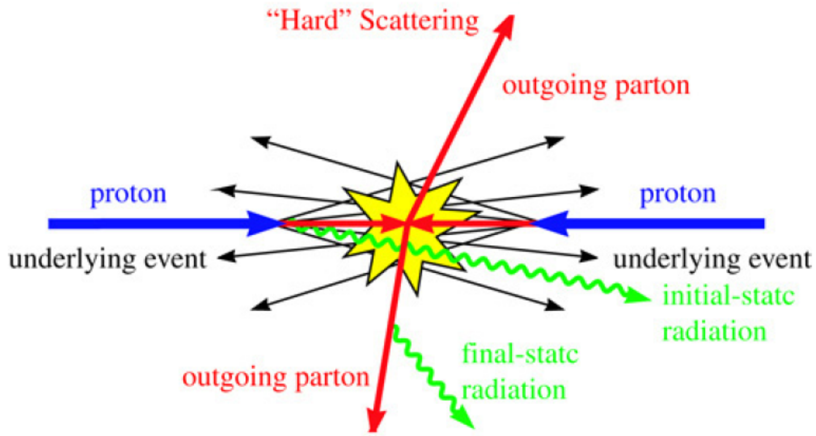
Michigan State University

for the QCD conveners

John Campbell, Ken Hatakeyama,
Frank Petriello

QCD

- QCD plays a major role in basically every physics process under discussion in the Snowmass workshop
- When we talk about precision physics, or discovery physics, we need to understand the role of QCD corrections



- Thus, we have an overlap, and hopefully a synergy, with every physics group in this workshop
- We have tried to exploit this synergy at the BNL meeting by having only joint sessions, with EWK, Higgs, top and QCD computing
  - we can talk to ourselves anytime
- Thus, there may be an overlap in slides, but hey I'm going first…

Charge

- The charge for the QCD group (like every other group) is to determine the
  1. current state of the art
  2. what is likely/priority for the next 5 years?
  3. what is likely/priority for longer time scale (20 years)?
- Of course a) is the easiest, b) is less so and parts of c) are in the realm of pure speculation
- We have broken down each question into a series of more definite sub-issues that should be addressed. For details, see my talk at the kickoff meeting at Fermilab.
- This talk will concentrate on issues discussed in this meeting, as well as those that have developed over the course of the last 6 months, both in Snowmass QCD meetings/discussion as well as in (pre-)Les Houches work

…keeping in mind not only the LHC, but…

A. hadron colliders

1. *LHC 13 TeV, 300/fb , spacing: 25 ns (50 ns), pileup: 19 (38) events/crossing*
2. *LHC 13 TeV, 3000/fb (HL-LHC) , spacing: 25 ns, pileup: 95 events/crossing*
3. *LHC 30 TeV, 3000/fb (HE-LHC) , spacing: 50 ns, pileup: 225 events/crossing*
4. *VHE-LHC 100 TeV, 3000/fb, spacing: 50 ns, pileup: 263 events/crossing*
5. *VLHC at 100 TeV, 1000/fb , spacing: 19 ns, pileup: 40 events/crossing*

future machines, especially hadron colliders

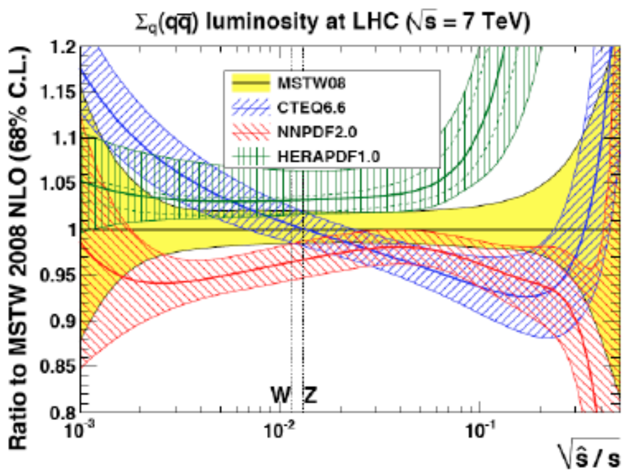
…sorry, not much work on linear colliders so far

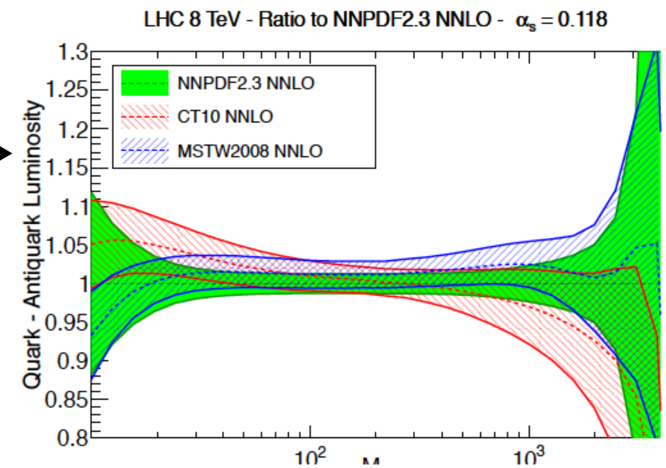
unitarity

pileup numbers are the average number of interactions per crossing at the peak luminosity, as explained

PDFs

- I gave a talk at this meeting on ‘PDFs for the LHC’ reporting specifically on some new benchmark results at NNLO (arXiv:1211.5142)



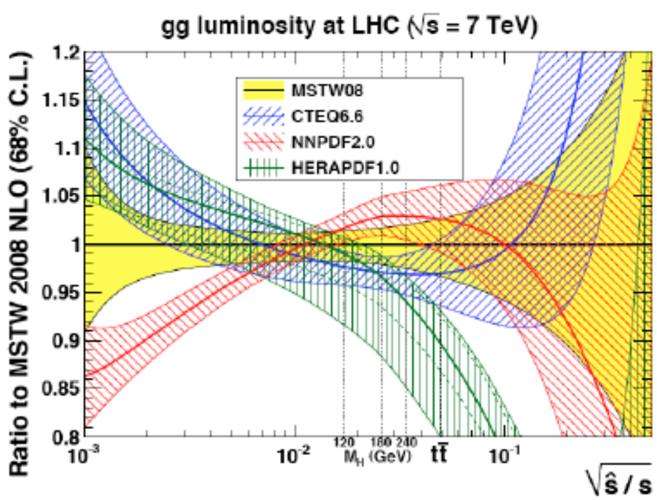


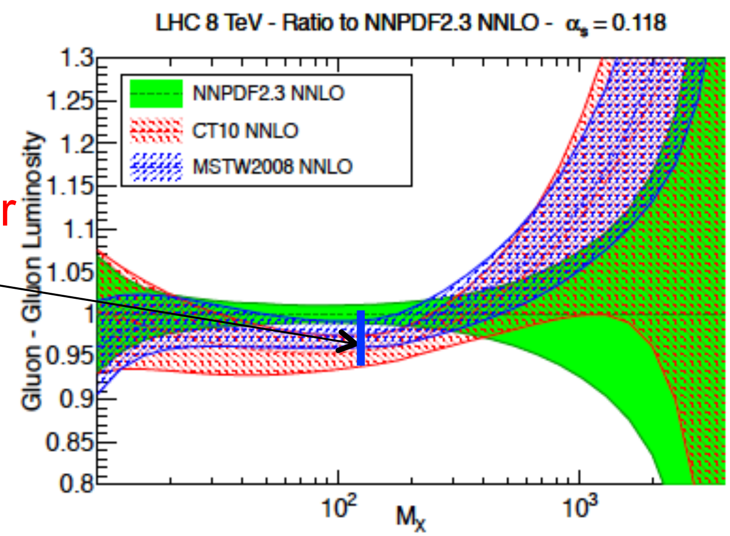
improvements from 2010 to 2012…

…and from NLO to NNLO

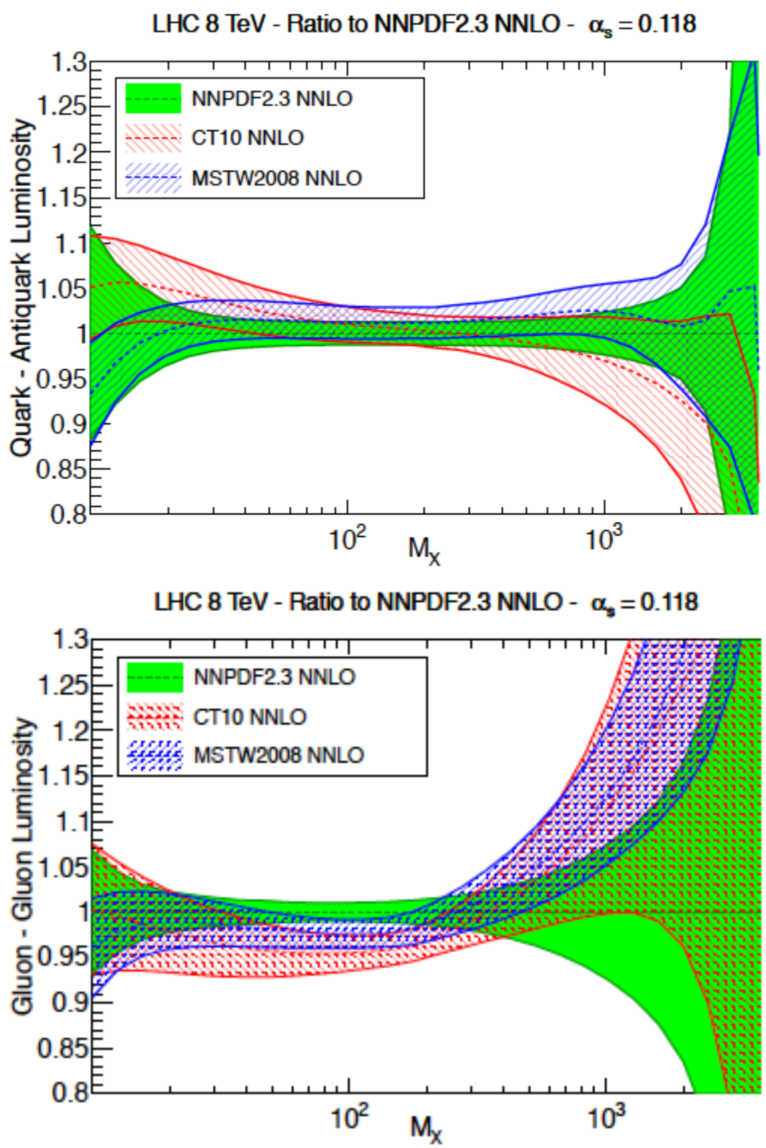
so Higgs PDF uncertainty under good control

α_S uncertainty still +/-0.002



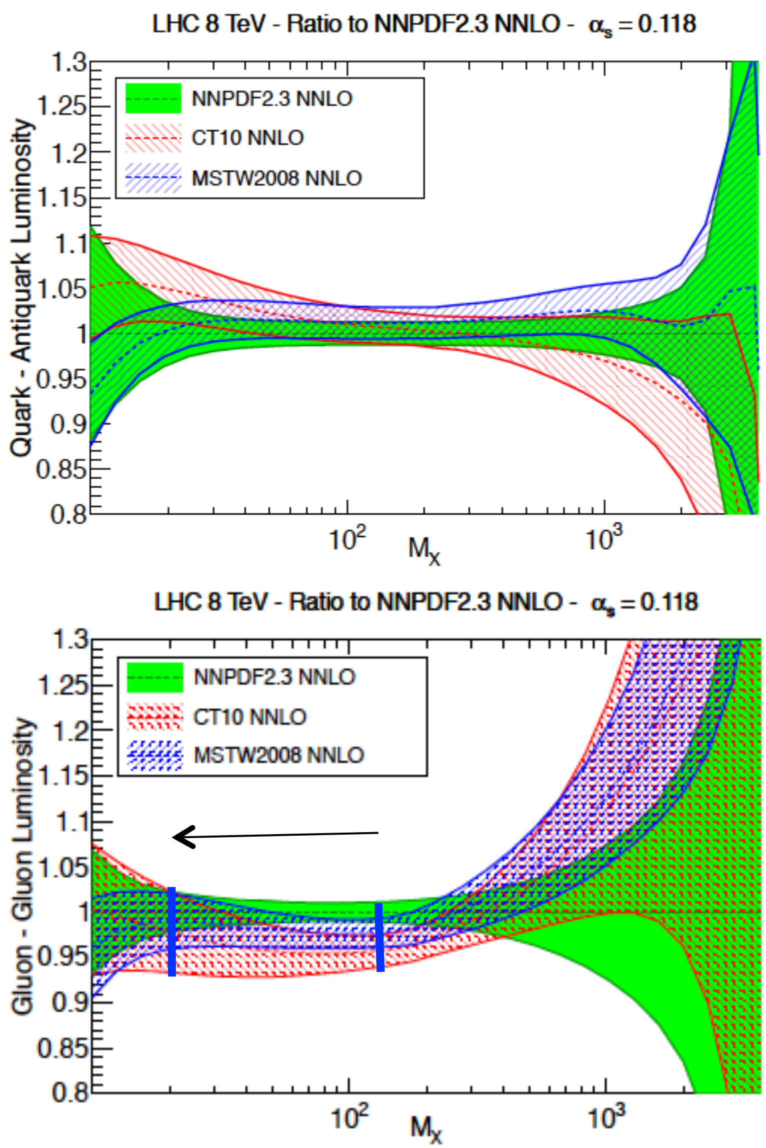


PDFs



- But what about at high mass?
- Are we going to believe a 50% excess at multi-TeV dijet masses, especially if we believe that it's produced by a gg initial state?
- These are 68% CL PDF errors
- We assume that we can extrapolate from 68% to 90%CL (CT PDF uncertainties actually performed at 90%CL)
- What about non-Gaussian behavior going to 95%, 98%?
- CT can use Lagrange Multiplier technique to look at this; NNPDF can use their Monte Carlo approach
- This is something we will do for the Snowmass report

PDFs



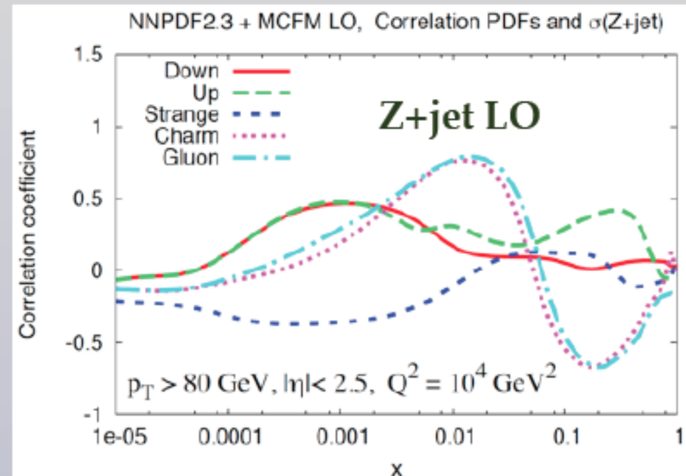
- What about uncertainties for higher energies
  - 13 TeV
  - 33 TeV
  - 100 TeV
- To first order, can just rescale horizontal axis for the plots to the left
  - but uncertainties do decrease with increasing Q^2
- So this is an approximation of the gg uncertainty for gg->Higgs (125 GeV) at 33 TeV
- We can calculate exactly the uncertainties for the different energies
- This is something we will do for the Snowmass writeup

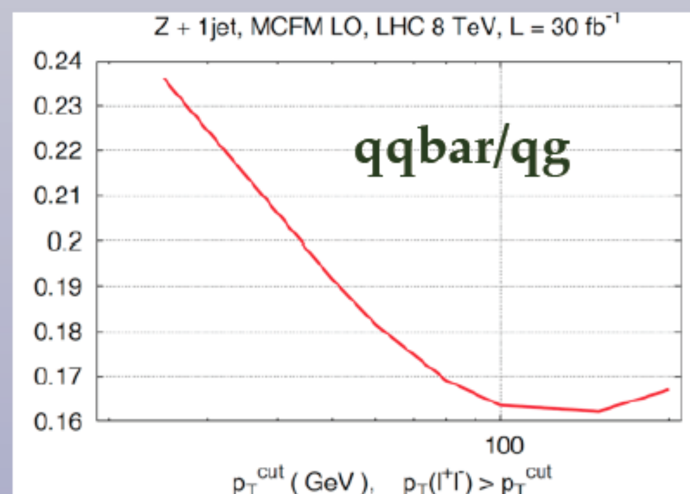
Using LHC data to improve PDF precision

New avenues to the gluon (I)

- In global PDF fits, the **gluon** is directly constrained by **jet data** only (and HERA at small-x)
- Jets are NLO with **large scale uncertainties** (though NNLO close, **arxiv:1301.7310**), and experimental errors substantial because of the **JES**
- Given the crucial role of the gluon for LHC physics, **complementary LHC observables directly sensitive the gluon** would be beneficial
- One possibility is **Z/W boson production at large pT** (in association with jets). Cross section > 80% **dominated by gluon-quark scattering** (ISR of extra jets gluon dominated)
- The measurement can be only with leptons (double differential in pT and rapidity), thus with **very small systematic errors**
- Statistical errors will be negligible
- This measurement will be equivalent to **measuring the partonic luminosity relevant for gg > H**

correlated systematic error information crucial





…and the experimental precision achieved for tT production at the LHC, plus the completion of the NNLO tT cross section means that top production is an important PDF benchmark

…but we need NNLO tT differential cross sections for full exploitation

Uta Klein: Drell-Yan

What may we have with 100 fb^{-1} …

✓ We may anticipate for 100 fb^{-1} NC and CC DY data over a wide kinematic range of 60 to 1500 GeV with negligible stat. precision (well <0.1%) around the peak region up to 5% at M~ 1 TeV while the systematic uncertainties are expected to be ½ of the present systematic uncertainties, e.g. for NC DY in the range of 0.5% at the peak up to 5% at high masses

➔ exploring more and more fully the data driven background estimates and the tag and probe based efficiency calculations (significant reduction of stats. component of the systematic uncertainty).

However, with increased statistics, and such small level of systematic uncertainties there may be also NEW effects at the sub-percent level 'discovered'.

…no real improvement in α_s uncertainty, though, IMHO

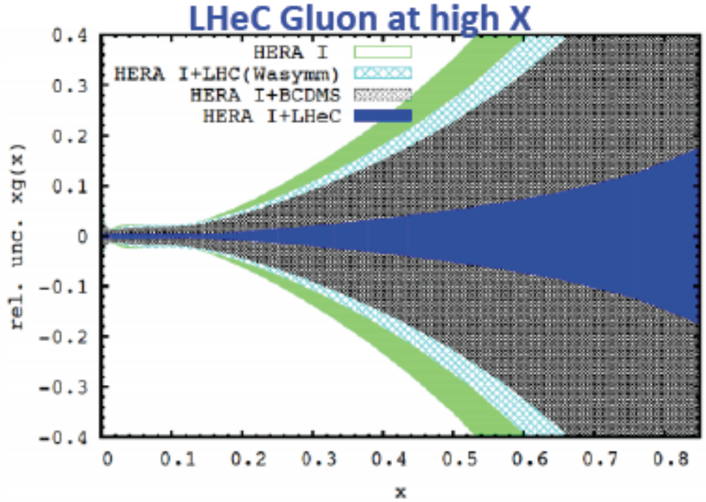
Do we need an LHeC?

PDFs at the LHeC

- PDFs are essential for precision physics at the LHC :
  - **one of the main theory uncertainties in Higgs production**
  - Measurements at high pT, high invariant masses, sensitive to new physics effects, have significant PDF uncertainties (high x)

- LHeC could provide a complete PDF set with precise gluon, valence at high x, as well as strong coupling

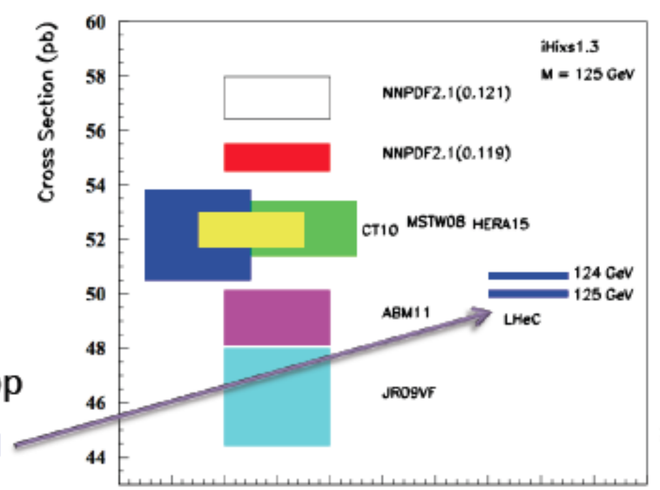
LHeC Gluon at high X



LHeC promises per mille accuracy on alphas!

case	cut $[Q^2$ in GeV$^2]$	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

NNLO pp−Higgs Cross Sections at 14 TeV



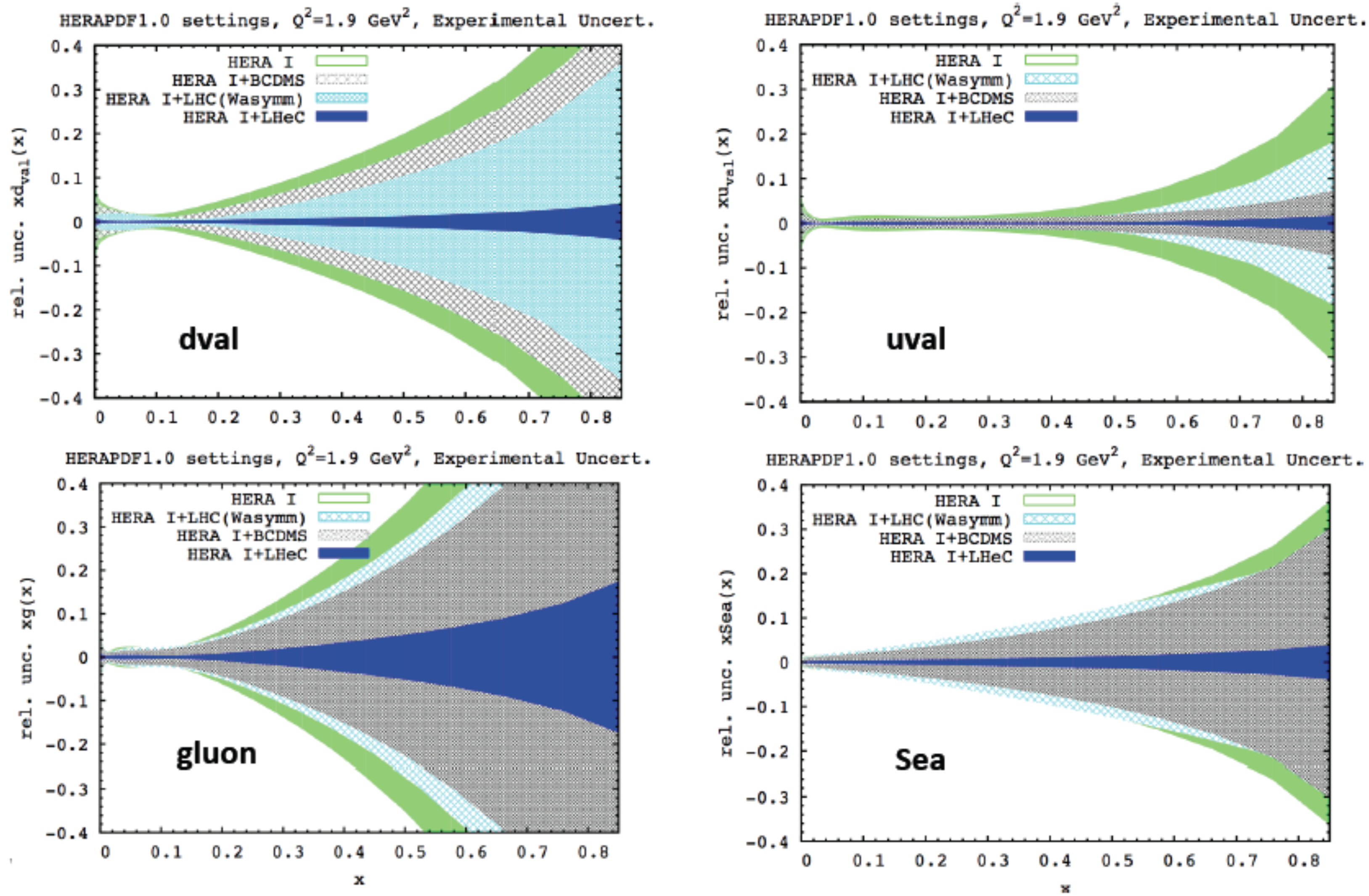
At the LHeC , Higgs is cleanly produced via ZZ or WW fusion, complementary to the dominant gg fusion at pp

- precision from LHeC can add a significant constraint on MH

Voica Radescu (see also Max Klein at https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=226756)

Impact of LHeC on PDFs: zoom on high x

* Experimental uncertainties are shown at the starting scale Q^2=1.9 GeV^2



- Les Houches NLO wishlist, started in 2005, and incremented in 2007 and 2009 was officially closed in 2011, since all of the calculations on the list were complete, and there are no technical impediments towards calculations of new final states, either with dedicated or semi-automatic calculations
- Note that dedicated calculations can be factors of 10 faster than semi-automatic

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30] WZ jet, $W\gamma$ jet completed by Campanario et al. [31, 32]
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [33]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [34, 35] Interference QCD-EW in VBF channel [36, 37]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [38] and WWZ by Hankele/Zeppenfeld [39], see also Binoth/Ossola/Papadopoulos/Pittau [40] VBFNLO [41, 42] meanwhile also contains $WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma,$ $\gamma\gamma\gamma, W\gamma\gamma j$ [43, 44, 45, 46, 47, 21]
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [48, 49] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [50]
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa [51] and Rocket [52] collaborations Z+3jets by Blackhat/Sherpa [53]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [54, 55]
7. $pp \to VV\, b\bar{b}$,	Pozzorini et al.[25],Bevilacqua et al.[23]
8. $pp \to VV$+2jets	W^+W^++2jets [56], W^+W^-+2jets [57, 58], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [59, 60, 61]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [62, 63]
NLO calculations added to list in 2009	
10. $pp \to V$ + 4 jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [64] for $W + n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also completed:	
$pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld [21]
$pp \to$ 4 jets	Blackhat/Sherpa [19]

6

Table 1: The updated experimenter's wishlist for LHC processes

For Snowmass report

- Calculate cross sections (LO and NLO, and in some cases NNLO) and uncertainties for a number of benchmark cross sections for higher energy pp accelerators
- Use MCFM for starters

What's next for the Les Houches NLO wishlist?

- Nothing: I've retired the NLO wishlist
- It's being replaced by a NNLO wishlist plus a wishlist for EW corrections for hard processes

Below we construct a table of calculations needed at the LHC, and which are feasible within the next few years. Certainly, results for inclusive cross sections at NNLO will be easier to achieve than differential distributions, but most groups are working towards a partonic Monte Carlo program capable of producing fully differential distributions for measured observables.

- $t\bar{t}$ production: done
  needed for accurate background estimates, top mass measurement, top quark asymmetry (which is zero at tree level, so NLO is the leading non-vanishing order for this observable, and a discrepancy of theory predictions with Tevatron data needs to be understood). Several groups are already well on the way to complete NNLO results for $t\bar{t}$ production [84, 85, 86, 87].
- W^+W^- production:
  importand background to Higgs search. At the LHC, $gg \to WW$ is the dominant subprocess, but $gg \to WW$ is a loop-induced process, such that two loops need to be calculated to get a reliable estimate of the cross section. Advances towards the full two-loop result are reported in [88, 89].
- inclusive jet/dijet production: gg done; full by end of year?
  NNLO parton distribution function (PDF) fits are starting to become the norm for predictions and comparisons at the LHC. Paramount in these global fits is the use of inclusive jet production to tie down the behavior of the gluon distribution, especially at high x. However, while the other essential processes used in the global fitting are known to NNLO, the inclusive jet production cross section is only known at NLO. Thus, it is crucial for precision predictions for the LHC for the NNLO corrections for this process to be calculated, and to be available for inclusion in the global PDF fits. First results for the real-virtual and double real corrections to gluon scattering can be found in [90, 91].

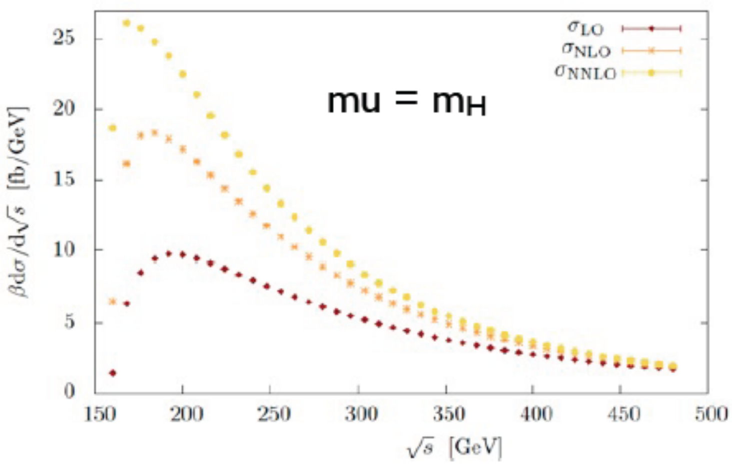
NNLO wishlist: continued

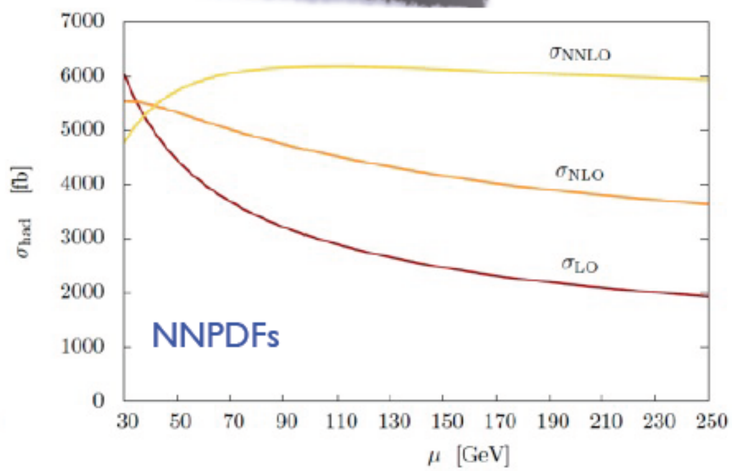
- V+1 jet production: <2 years
  $W/Z/\gamma$ + jet production form the signal channels (and backgrounds) for many key physics processes, for both SM and BSM. In addition, they also serve as calibration tools for the jet energy scale and for the crucial understanding of the missing transverse energy resolution. The two-loop amplitudes for this process are known [92, 93], therefore it can be calculated once the parts involving unresolved real radiation are available.
- V+γ production: by end of year?
  important signal/background processes for Higgs and New Physics searches. The two-loop helicity amplitudes for $q\bar{q} \to W^{\pm}\gamma$ and $q\bar{q} \to Z^0\gamma$ recently have become available [94].
- Higgs+1 jet production: gg done; full by end of year?
  As mentioned previously, events in many of the experimental Higgs analyses are separated by the number of additional jets accompanying the Higgs boson. In many searches, the Higgs + 0 jet and Higgs + 1 jet bins contribute approximately equally to the sensitivity. It is thus necessary to have the same theoretical accuracy for the Higgs + 1 jet cross section as already exists for the inclusive Higgs cross section, i.e. NNLO. The two-Loop QCD Corrections to the Helicity Amplitudes for $H \to 3$ partons are already available [95].

Radja Boughezal

arXiv:1303.4405

H+jet @ NNLO: gg-channel





$$\sigma_{\rm LO}(pp \to Hj) = 2713^{+1216}_{-776}\ {\rm fb},$$
$$\sigma_{\rm NLO}(pp \to Hj) = 4377^{+760}_{-738}\ {\rm fb},$$
$$\sigma_{\rm NNLO}(pp \to Hj) = 6177^{-204}_{+242}\ {\rm fb}.$$

$\sigma_{NLO}/\sigma_{LO} = 1.6$

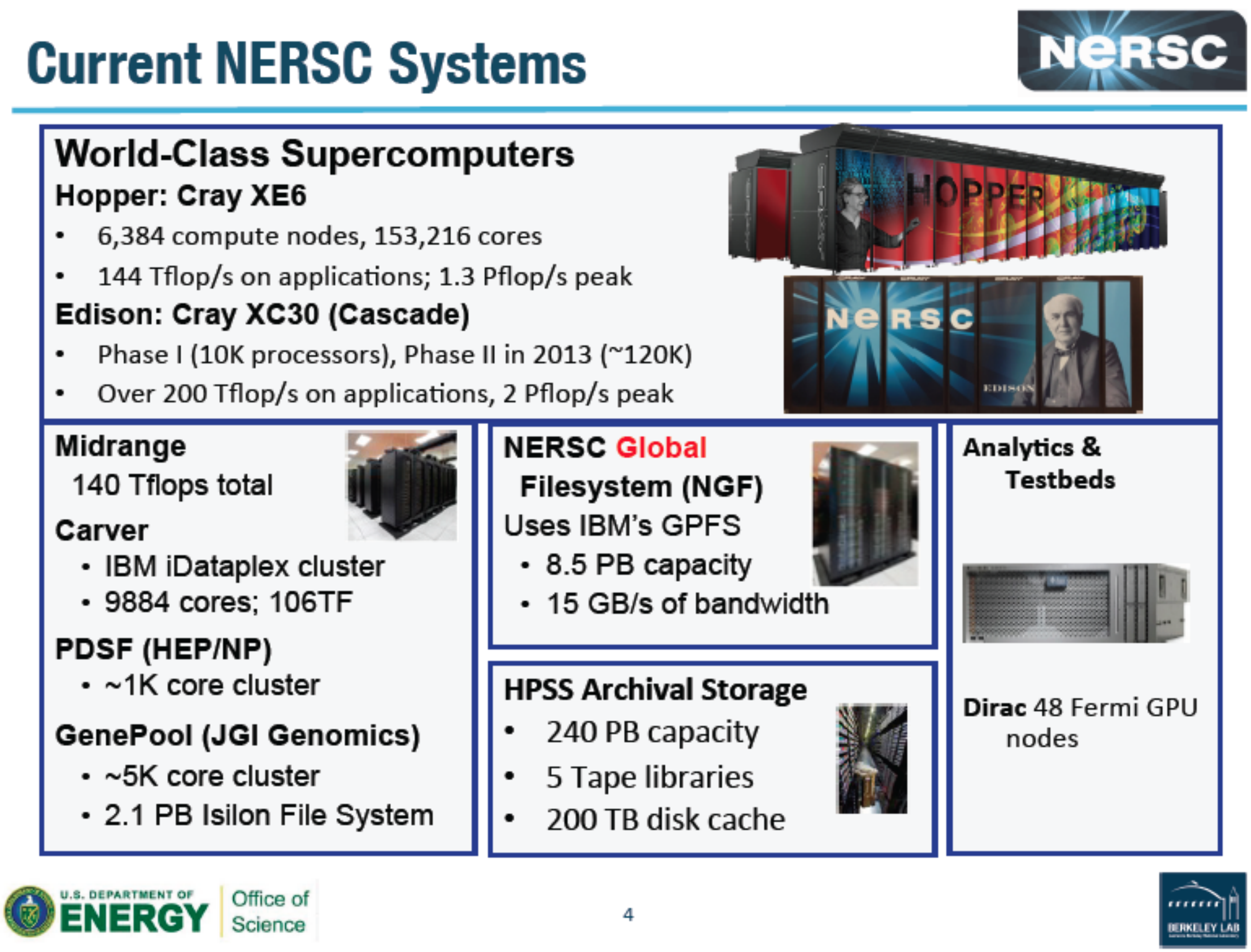
$\sigma_{NNLO}/\sigma_{NLO} = 1.3$

so sizeable increase of cross section in going to NNLO

clear implications for Higgs+jets studies going on by ATLAS and CMS

what can we guess for Higgs + 2 jets?

Richard Gerber



higher order calculations very CPU-intensive

we're not making as much use of existing HPC resources as we could

Higgs+jets (binned cross sections)

Uncertainties

Jianming Qian

Scale uncertainties of cross sections in exclusive jet bins are calculated

- assuming uncertainties of inclusive jet cross sections

  $\varepsilon_{\geq 0}, \quad \varepsilon_{\geq 1}, \quad \varepsilon_{\geq 2}$

  are independent (Stewardt and Tackmann: Phys. Rev. D85 (2012) 034011)
- and propagated from the following equations

$$\sigma_0 = \sigma_{\geq 0} - \sigma_{\geq 1}; \quad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}; \quad \sigma_2 = \sigma_{\geq 2}$$

The actual implementation is described in the joint ATLAS/CMS note:
ATL-PHYS-PUB-2011-818

Procedure for the LHC Higgs boson search combination in summer 2011

(LHC Higgs Combination Group Report)

The ATLAS and CMS collaboration and the Higgs Combination group

July 20, 2011

since cross sections are uncorrelated, add in quadrature

125 GeV at 8 TeV with ATLAS jet selection

jet bin (n)	jet fraction (f_n)	Uncertainties Inclusive ($\epsilon_{\geq n}$)	Uncertainties Exclusive (ϵ_n)
$n=0$	0.614	0.078	$\boxed{0.170}$
$n=1$	0.267	0.202	$\boxed{0.370}$
$n=2$	0.119	0.697	$\boxed{0.697}$

(Uncertainties are symmetrized in the implementation)

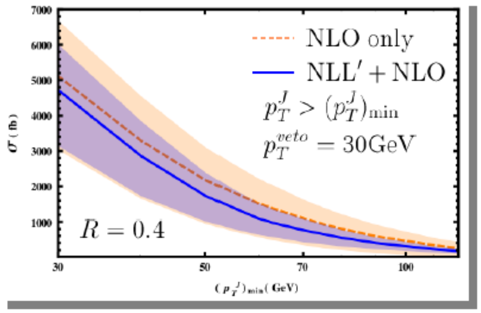
uncertainties for exclusive (fixed order) cross sections can be much larger than for inclusive cross sections

Higgs+jets (binned cross sections)

Progress

Xiaohui Liu

- Numerical consequence
  - Higgs + 1j
    - Entire Spectrum
      - Conservative error estimation
      - Up to 25% reduction in the uncertainty



resummation for Higgs + 0 jet and for Higgs + 1 jet has lead to sizeable reduction in scale uncertainty

m_H (GeV)	p_T^{veto} (GeV)	$\sigma_{\rm NLO}$ (pb)	$\sigma_{\rm NLL'+NLO}$ (pb)	$f^{1j}_{\rm NLO}$	$f^{1j}_{\rm NLL'+NLO}$
124	25	$5.92^{+35\%}_{-46\%}$	$5.62^{+29\%}_{-30\%}$	$0.299^{+38\%}_{-49\%}$	$0.283^{+33\%}_{-34\%}$
125	25	$5.85^{+34\%}_{-46\%}$	$5.55^{+29\%}_{-30\%}$	$0.300^{+37\%}_{-49\%}$	$0.284^{+33\%}_{-33\%}$
126	25	$5.75^{+35\%}_{-46\%}$	$5.47^{+30\%}_{-30\%}$	$0.300^{+38\%}_{-49\%}$	$0.284^{+34\%}_{-33\%}$
124	30	$5.25^{+31\%}_{-41\%}$	$4.83^{+29\%}_{-29\%}$	$0.265^{+35\%}_{-43\%}$	$0.244^{+33\%}_{-33\%}$
125	30	$5.19^{+32\%}_{-41\%}$	$4.77^{+30\%}_{-29\%}$	$0.266^{+35\%}_{-43\%}$	$0.244^{+33\%}_{-33\%}$
126	30	$5.12^{+32\%}_{-41\%}$	$4.72^{+30\%}_{-29\%}$	$0.266^{+35\%}_{-43\%}$	$0.246^{+33\%}_{-32\%}$

15

XL and Petriello'12, XL and Petriello'13

we need to revisit the formulation of the uncertainties for binned jet Higgs cross sections

this is a task for Snowmass/ Les Houches

also investigate jet veto effects for higher energy accelerators

ımmary

- Formalism to understanding jet bin cross section has been established (not only Higgs)
- More reliable prediction and reduced theory uncertainty
- Error estimation should be revised using the resummed results for higgs + 0j and higgs +1j
- Fine tuning work worth probing (higher accuracy, log(R) issue, non-global logs, etc..)

NLO ME+PS

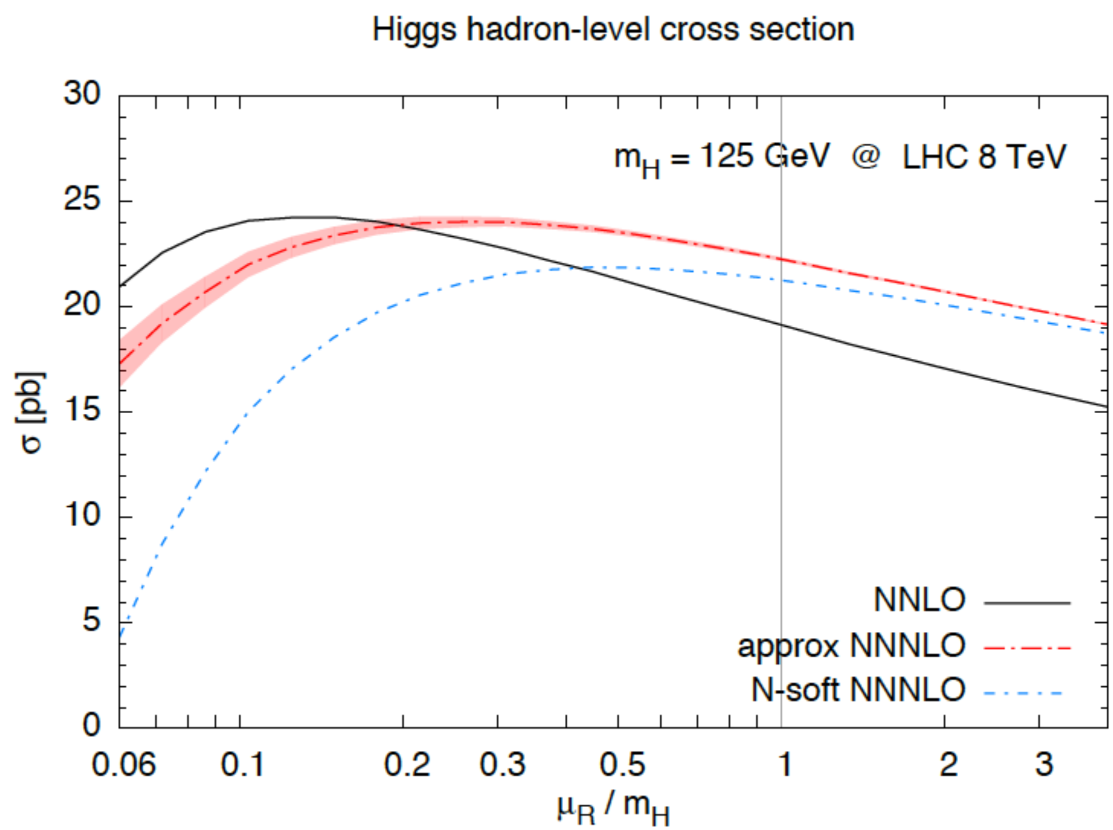
- There are several frameworks now, such as Sherpa and aMC@NLO, in which multiple jets can be included at NLO, with additional jets at LO, with additional additional jets via the parton shower
- For example, Higgs + 0, 1 and 2 jets at NLO, with up to 3 additional jets at LO (matrix element) in Sherpa
- The result is a MC dataset similar to what is seen in the data, with a NLO(+NLL) accuracy
- This is a good framework to try to further understand Higgs cross sections plus their uncertainties
- Snowmass + Les Houches project->do the above

Beyond NNLO

- Note the considerable flattening of the scale uncertainty at approximate NNNLO
- Note also the importance of including BFKL logs in addition to soft logs
- Note also that the net result is an increase in the (gg->) Higgs cross section that we currently use for our comparisons
- Snowmass+Les Houches project: investigate effects of BKFL logs in resummation for the higher energy accelerators, plus the explicit expected effects of BFKL logs in hard scattering processes, a la HEJ, compared to fixed order predictions for multi-jet final states, such as from Blackhat+Sherpa

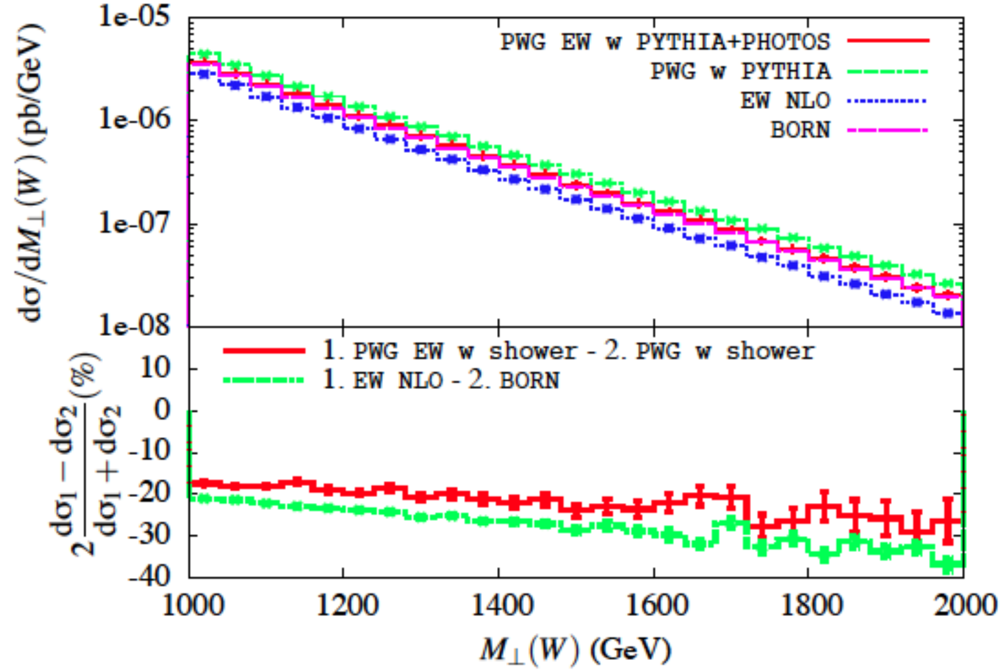
Plot produced by Marco Bonvini

Paper=='Higgs production in gluon fusion beyond NNLO', R. Ball et al; arXiv:1303.3590



QCD+EWK

- How well do we know the DY cross section for a mass of 2 TeV?
- Would we recognize a real deviation from SM, say a broad resonance, if we saw it?



Brookhaven, Ap

Uta Klein

A wish list for discussion & studies

.. some tasks are already under study also in LPCC and EW experimental and theory WG's

- ❖ Numerical stability of NNLO and NLO calculations, e.g. issues related to choice of symmetric p_T cuts, intrinsic integration settings, and the case of fine bins and high precision (→ smaller than exp. uncertainties, so <0.5% per bin), etc.
- → "optimal" choice (and documentation) of EW parameters and SM inputs
- → high precision (<0.1% per bin) "APPLgrids at NNLO" .. ?
- ❖ Precision evaluation of missing HO EW (ISR, interferences, weak) corrections and QED FSR modelling; application of missing HO EW corrections and remaining systematics
- ❖ Uncertainties due to further missing HO QCD effects as usually estimated by "scale uncertainties" → realistic prescription for NNLO (CPU time!)
- ❖ Improved modelling of p_T(W,Z) : implementation of resummation into NLO MC models (but e.g also control of resummation scale)
- ❖ Improved modelling and measurement proposals for non-resonant photon-induced dilepton productions, but also for the NLO gamma-p induced dilepton and W productions
- ❖ Improved modelling of real W and Z radiation beyond LO approach outlined by U.Baur, arXiv:hep-ph/0611241

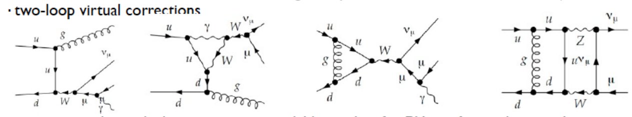
QCD+EWK effects

A. Vicini: there has been a great deal of progress in the last few years, but all of the separate pieces have not been put together in a common framework, allowing a 'best' estimate of cross sections and uncertainties

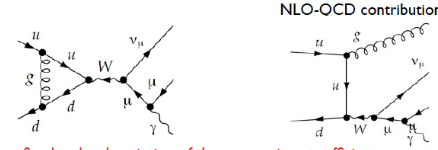
Mixed QCDxEW corrections the Drell-Yan cross section

$$\sigma_{tot} = \sigma_0 + \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \dots + \alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \dots + \boxed{\alpha\alpha_s\,\sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2\,\sigma_{\alpha\alpha_s^2} + \dots$$

- The first mixed QCDxEW corrections include different contributions:
  - emission of two real additional partons (one photon + one gluon/quark)
  - emission of one real additional parton (one photon with QCD virtual corrections, one gluon/quark with EW virtual corrections)
  - two-loop virtual corrections



- an exact complete calculation is not yet available, neither for DY nor for single gauge boson production
  W.B. Kilgore, C. Sturm, arXiv:1107.4798
- The bulk of the mixed QCDxEW corrections, relevant for a precision MW measurement, is factorized in QCD and EW contributions:
  (leading-log part of final state QED radiation) X (leading-log part of initial state QCD radiation || NLO-QCD contribution to the K-factor)



In any case, a fixed order description of the process is not sufficient...

Alessandro Vicini - University of Milano Brookhaven, April 4th 2013 9

Perturbative expansion of the Drell-Yan cross section

$$\begin{aligned}\sigma_{tot} = \sigma_0 &+ \boxed{\alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2}} + \dots \\ &+ \boxed{\alpha\sigma_\alpha} + \boxed{\alpha^2\sigma_{\alpha^2}} + \dots \\ &+ \boxed{\alpha\alpha_s\,\sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2\,\sigma_{\alpha\alpha_s^2} + \dots\end{aligned}$$

Fixed order corrections exactly evaluated and available in simulation codes

Subsets of corrections partially evaluated or approximated

$O(\alpha^2)$

- EW Sudakov logs J.Kühn, A.Kulesza, S.Pozzorini, M.Schulze, Nucl.Phys.B797:27-77,2008, Phys.Lett.B651:160-165,2007, Nucl
- QED LL
- QED NLL (approximated)
- additional light pairs (approximated)

O(αα_s)

- EW corrections to ffbar+jet production
- QCD corrections to ffbar+gamma production

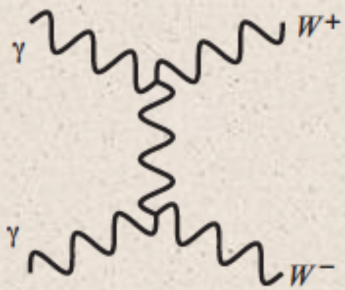
A.Denner, S.Dittmaier, T.Kasprzik, A.Mueck, arXiv:0909.39

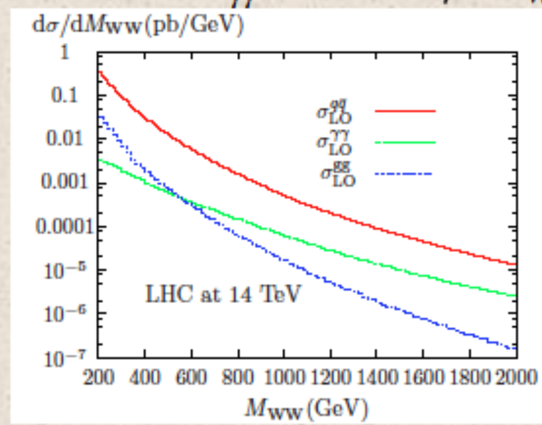
Les Houches project: put those pieces together

Photon PDFs: Carl Schmidt

2) Photon induced processes can be kinematically enhanced.

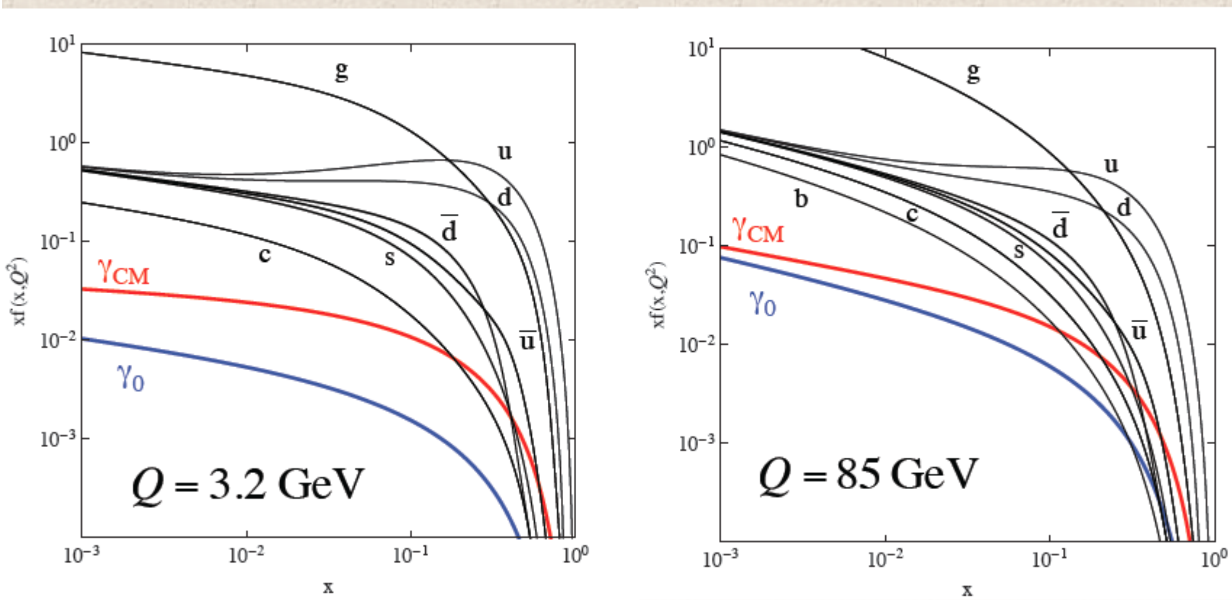
$$\gamma\gamma \to W^+W^- \quad \text{asymptotically} \quad \hat{\sigma}_{\gamma\gamma} \approx 8\pi\alpha^2/M_W^2$$





significant fraction of high mass WW pairs from γγ, even after kinematic cuts

Bierweiler et al., JHEP 1211 (2012) 093



photon PDFs can be larger than anti-quarks at high x

the LHC (and higher energy machines) is a γγ factory

Snowmass+Les Houches project: investigate this

The future looks bright

- …but the future also looks busy
- Given the schedule presented, much of this work needs to be done before Les Houches (June 3-23)
- We'll be calling you
- But much of it will also be done at Les Houches and after
- And if it doesn't make it into the Snowmass report, it will make it into the Les Houches proceedings
  - ~Feb 2014
- Our next meeting will be after Loopfest on May 16 (Florida State)
- I'll also try to organize a meeting from Les Houches